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Impacts of management practices on bioenergy feedstock yield and economic feasibility on Conservation Reserve Program grasslands

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Abstract

Perennial grass mixtures planted on Conservation Reserve Program (CRP) land are a potential source of dedicated bioenergy feedstock. Long-term nitrogen (N) and harvest management are critical factors for maximizing biomass yield while maintaining the longevity of grass stands. A six-year farm-scale study was conducted to understand the impact of weather variability on biomass yield, determine optimal N fertilization and harvest timing management practices for sustainable biomass production, and estimate economic viability at six CRP sites in the United States. Precipitation during the growing season was a critical factor for annual biomass production across all regions, and annual biomass production was severely reduced when growing season precipitation was below 50% of average. The N rate of 112 kg ha^{-1} produced the highest biomass yield at each location. Harvest timing resulting in the highest biomass yield was site-specific and was a factor of predominant grass type, seasonal precipitation, and the number of harvests taken per year. The use of N fertilizer for yield enhancement unambiguously increased the cost of biomass regardless of the harvest timing for all six sites. The breakeven price of biomass at the farmgate ranged from \$37 to \$311 Mg^{-1} depending on the rate of N application, timing of harvesting, and location when foregone opportunity costs were not considered. Breakeven prices ranged from \$69 to \$526 Mg^{-1} when the loss of CRP land rental payments was included as an opportunity cost. Annual cost of the CRP to the federal government could be reduced by over 8% in the states included in this study; however, this would require the biomass price to be much higher than in the case where the landowner receives the CRP land rent. This field research demonstrated the importance of long-term, farm-scale research for accurate estimation of biomass feedstock production and economic viability from perennial grasslands.

Keywords: biomass, breakeven price, cool-season mixture, harvest management, nitrogen management, opportunity cost, perennial grasses, warm-season mixture

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Introduction

The Conservation Reserve Program (CRP) is a land retirement program established by the Food Security Act of 1985 (Food Security Act of 1985; Glaser, 1986). The goals of this program were to protect environmentally sensitive land and, to a lesser extent, to reduce production of cash crops in order to stabilize commodity prices. These lands are potentially a major resource for cellulosic biofuel feedstock production (USDOE 2011), and up to 10 million ha of CRP grassland could be dedicated to bioenergy feedstock production from which biomass production of approximately 50 million dry metric tons could be expected annually (Perlack *et al.*, 2005).

Total land enrolled in the CRP has decreased by nearly 4.5 Mha since 2007, mainly due to the loss of

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existing grasses and legumes (USDA-FSA, 2015). In the Western Corn Belt alone (ND, SD, NE, MN, and IA), total conversion of grassland to conventional cropping systems from 2006 to 2011 was estimated to be 530 000 ha (Wright & Wimberly, 2013). Recent annual wetland loss rate in the Dakota Prairie Pothole Region, an area of particular concern for wildlife preservation, was estimated to be between 0.28 and 0.35% (5203–6223 ha yr^{-1}) due to row crop expansion (Johnston, 2013). One reason for these declines was the rise in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] prices from 2006 to 2013, which attracted growers away from reserve programs with the prospects of greater revenues. If corn and soybean prices were to increase again in the future, an incremental increase in CRP land leaving the program is predicted—this would likely bring more environmentally fragile land into production with the likely outcome of reduced environmental quality (Secchi *et al.*, 2009). Increased prices for corn may result in the decline in lands under CRP contracts in the Northern Great Plains (Fargione *et al.*, 2009), although grassland conversion to corn and soybean cropping has exceeded the amount of land area lost from CRP in the eastern portions of the Dakotas and Nebraska (Wright & Wimberly, 2013). Total CRP enrollment as of September 2015 was 9.8 Mha, and contracts incorporating 2.8 Mha of CRP land expire between 2015 and 2018 (USDA-FSA, 2015).

Numerous benefits are reported of perennial bioenergy feedstock production compared with conventional row crop production systems. Impacts of conversion of CRP grasslands to conventional cropping systems on soil and water quality are more certain and assumed to be more negative than impacts from conversion to managed second-generation (i.e., cellulosic) bioenergy feedstocks (Clark *et al.*, 2013). Periodic harvesting of biomass in CRP grasslands may be a beneficial method of removing litter buildup that can reduce the benefits to certain wildlife species, particularly if burning is not a viable option (Venuto & Daniel, 2010). Other benefits of perennial grasses include increasing soil organic matter (Burke *et al.*, 1995; Lee *et al.*, 2007a,b), increasing biodiversity and wildlife conservation (Fargione *et al.*, 2009; Meehan *et al.*, 2010; Wright & Wimberly, 2013), and positive energy and greenhouse gas (GHG) balances (Tilman *et al.*, 2006; Schmer *et al.*, 2008; Gelfand *et al.*, 2011, 2013; Georgescu *et al.*, 2011). Harvesting biomass on a successional old-field system with N fertilization achieved energy production rates comparable to those with no-till continuous corn cropping (62 GJ ha^{-1} yr^{-1}), with much better net GHG balances (−932 and −344 g CO_{2eq} m^{-2} yr^{-1}, respectively) (Gelfand *et al.*, 2013). Ruan & Robertson (2013) found that N_2O and CO_2 emissions in the initial period following conversion of CRP fields in Michigan to soybean were much higher using conventional tillage compared with no-till practices, and both systems resulted in substantially greater emissions than in the undisturbed CRP field. Gelfand *et al.* (2011) expected a C debt when converting CRP grassland to managed perennial grasses during the transition period while Follett *et al.* (2009) detected no significant changes in soil organic C over 6 years when converting from smooth bromegrass (*Bromus inermis* Leyss) to no-till corn production.

Degraded and sensitive lands of drier regions are unlikely to produce appreciable biomass yields, given the reduced harvest frequency allowed under CRP contracts. Juneja *et al.* (2011) estimated that < 242 L ethanol ha^{-1} could be expected annually from CRP land in eastern Oregon and Washington if harvested every 10 years, which is the allowed harvesting frequency on CRP land in this region because of the dry climate. Modeling has shown that easing restrictions on harvest frequency and widening the harvest window can greatly reduce feedstock production costs (Mapemba *et al.*, 2007). However, increasing harvest frequency may also reduce biomass production. Annual harvesting without the addition of fertilizer caused a linear decline in biomass production in a three-year Oklahoma study (Venuto & Daniel, 2010), yet Mapemba *et al.* (2007) assumed no fertilization was necessary to maintain biomass productivity on CRP lands when harvested every second or fourth year.

The Farm Security and Rural Investment Act of 2002 (a.k.a., 2002 Farm Bill) permitted managed haying, grazing, and biomass harvesting of CRP grassland in accordance with a conservation plan (Farm Security and Rural Investment Act of 2002, 2002; Mapemba *et al.*, 2007). These harvests, however, were subject to limitations in frequency and timing during the year. The Food, Conservation, and Energy Act of 2008 (a.k.a., 2008 Farm Bill), Title II, Subtitle B allowed harvests for forage or biomass after the primary nesting season for grass-nesting birds (USDA 2008), and other restrictions apply (USDA-FSA 2011). Participants accept a 25% reduction in CRP land rental payment during years when biomass is hayed, grazed, or harvested for biomass (USDA-FSA 2011).

Production of perennial cellulosic bioenergy feedstocks on CRP land may provide a means to meet the goals of the program while providing landowners additional revenue. Decisions to convert CRP land would be based on expected biomass revenue minus income from program payments (Khanna *et al.*, 2011). Therefore, these lands provide an excellent source of cellulosic feedstock without significant land-use changes while

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maintaining many of the original environmental benefits of the CRP (Chamberlain *et al*., 2011; Clark *et al*., 2013). With this in mind, the Sun Grant/US Department of Energy Regional Biomass Feedstock Partnership has identified grass mixtures planted in CRP lands as one of five herbaceous sources with potential as a dedicated bioenergy feedstock.

The overall goal of this study was to perform long-term, replicated field trials on CRP land to assess the yield potential and suitability of CRP grassland as a bioenergy feedstock source across logical regions of adaptation. One of the objectives of this project was to quantify effects of N fertilization and harvest timing on yield potential of CRP grassland grown in different environments using field-scale agricultural practices that are standard for each test region. The results from the first 3 years of this six-year study have been published (Lee *et al*., 2013). This study will present the results of the final 3 years and summarize the overall conclusions of the study. A second goal was to better estimate the effect of weather variability on biomass yield potential. A third goal was to examine the costs of biomass harvest on CRP land under alternative N fertilization and harvest timing scenarios. Our analysis has implications for CRP land owners regarding economic viability and the best management practice of biomass harvest and for the government regarding CRP rental payment management once CRP land is allowed for biomass production.

Materials and methods

Six established CRP grassland sites, one each in Georgia (GA), Kansas (KS), Missouri (MO), Montana (MT), North Dakota (ND), and Oklahoma (OK) U.S.A., were chosen for the study. Warm-season grasses were the predominant species in KS, ND, and OK while cool-season grasses were predominant at GA, MO, and MT. Site locations, soil types, soil analysis results, predominant individual biomass species, and site preparation procedures were outlined in Lee *et al.* (2013). Initial soil analyses were conducted at each site; P and K were adequate at all locations with the exception of low P (9 and 14 mg kg^{-1}) at KS and ND, respectively. All locations had been managed in accordance with CRP regulations, including no N fertilization and/or aboveground biomass harvest since the start of the contract until fall 2007. All field sites were selected in spring 2008 and mowed at a 10–15 cm height in the spring before imposing fertilization treatments.

The experimental design was a factorial arrangement of three urea N rates (0, 56, and 112 kg N ha^{-1}), applied annually in the spring using a farm-scale fertilizer spreader and two harvest timings (peak standing crop at anthesis, PSC, and the end of the growing season, EGS, which typically coincided with a killing frost) with three replicates at each location. The plot size for treatments was approximately 0.5 ha. Treatments were first applied in the spring of 2008 except in GA where no N was applied that year. Dates of fertilizer applications and biomass harvests are presented in Table 1. Precipitation data were recorded for each location for the duration of the study (Fig. 1).

Biomass yield was determined by harvesting whole plots using farm-scale equipment (mowing, raking, baling, and hauling) at a cutting height of 10–15 cm. For warm-season grass CRP sites, biomass was harvested annually either at PSC or EGS (Table 1). For cool-season CRP sites, biomass was harvested at PSC and/or EGS in a single-cut (MT) or two-cut (GA and MO) system. At MO, biomass in the PSC treatment was harvested at anthesis and again at the end of the growing season while the EGS treatment was harvested at maximum standing crop in the spring and again at the end of the growing season in the fall. At GA, EGS treatments included harvests both at PSC and EGS timing. Detailed harvest protocols for

Table 1 Dates for N applications and biomass harvests from 2011 to 2013

	N application			PSC*			EGS		
Location	2011	2012	2013	2011	2012	2013	2011	2012	2013
Warm-season grass locations									
KS	22-Mar	28-Mar	19-Mar	29-Jul	26-Oct	23-Jul	27-Oct	26-Oct	12-Nov
OK	5-Jun	18-Jun	18-Jun	n/a	25-Sep	12-Oct	n/a	22-Dec	14-Jan
ND	9-Jun	22-May	12-Jun	24-Aug	9-Aug	9-Aug	1-Nov	1-Oct	9-Oct
Cool-season grass locations									
MT	13-May	20-Apr	n/a	5-Jul	5-Jul	n/a	27-Oct	18-Oct	n/a
GA†	8-Apr	22-Mar	n/a	24-May	8-May	n/a	24-May/ 26-Oct	8-May/ 22-Oct	n/a
MO‡	18-Mar	15-Mar	18-Mar	2 Jun/ 17-Oct	14 May/ 22 Jun	4 Jun/ 27 Jun	27 Jul/ 17-Oct	22 Jun/ 29-Oct	27 Jun/ 8-Nov

*PSC, peak standing crop; at anthesis; EGS, end of growing season.
†PSC treatment was harvested in GA only at PSC while EGS treatment was harvested at both PSC and EGS.
‡Both harvest treatments in MO were two-cut systems—an early PSC harvest (anthesis) and a late PSC (maximum biomass accumulation) harvest; both were harvested again in autumn at the end of the growing season. The early PSC harvest plus the harvest at the end of the season was considered the PSC treatment while the late PSC harvest plus the harvest at the end of the season were considered as the EGS treatment in the analyses.

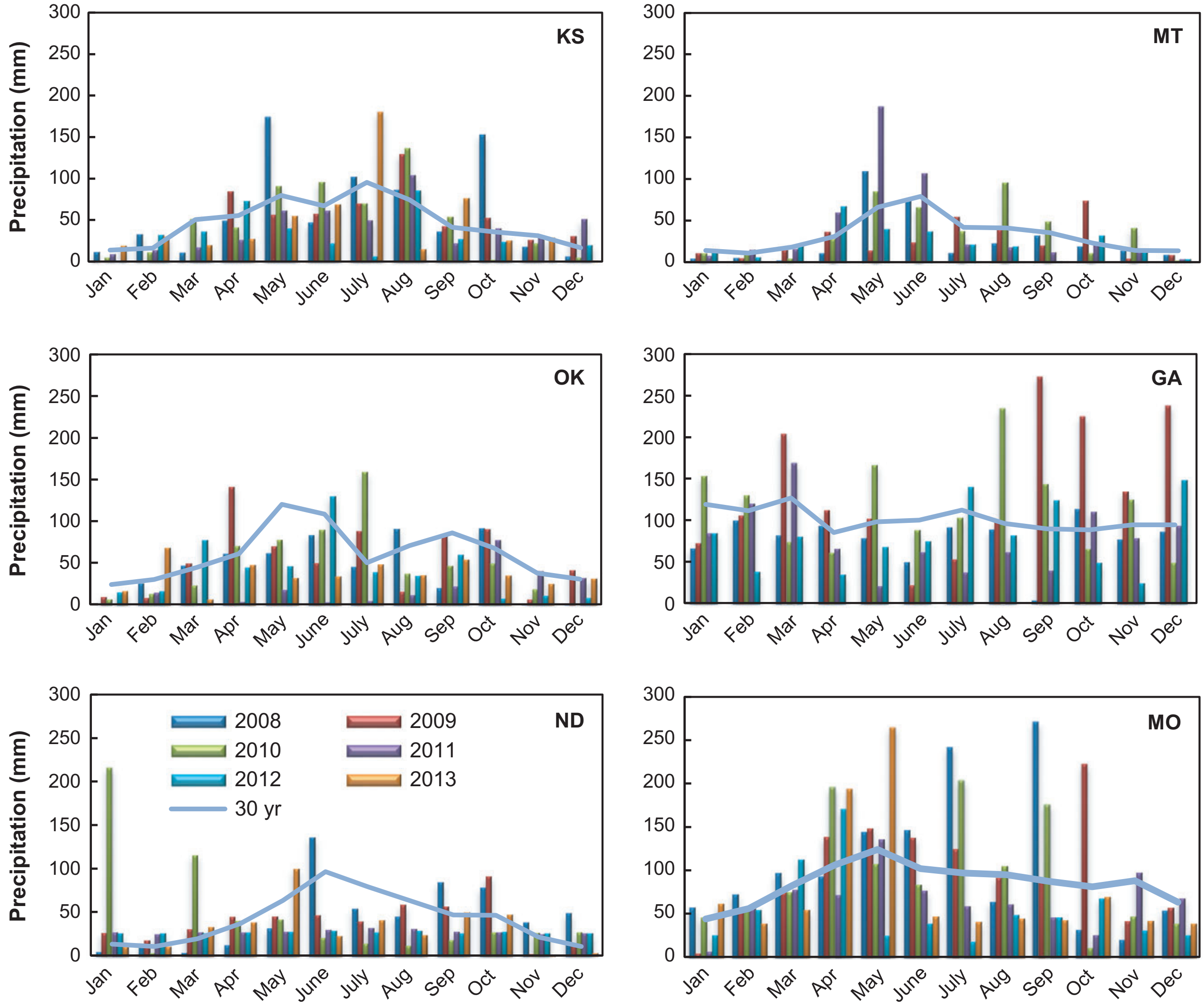

Fig. 1 Precipitation for 2008–2013 and the 30-year averages (1981–2010) for the warm-season grass (KS, OK, ND) and cool-season grass sites (MT, GA, MO).

each location were outlined in Lee *et al.* (2013). Aboveground biomass for each plot was baled with a large-round baler, weighed, and then subsampled. Subsamples were collected from bales using a core sampler (5 cm diameter and 50 cm long) attached to an electric drill and were dried at 60 °C for 48 h in a forced-air oven to determine percent moisture. No harvest was conducted in OK in 2011 due to insufficient biomass production caused by drought. Final harvests were made in 2012 in GA and MT and in 2013 at the remaining sites.

Normality of the residuals was evaluated using box plots in the UNIVARIATE procedure, and equality of the variances was evaluated using plots of the observed versus predicted residuals with SAS software (SAS Institute, 2012. The SAS System for Windows, Version 9.4. SAS Institute, Inc., Cary, NC, USA). Statistical analyses were performed using the PROC MIXED procedure in SAS with significant differences detected at $\alpha = 0.05$. Year, nitrogen rate, harvest timing, and the interaction terms were considered fixed variables while block was considered a random variable. Locations were analyzed separately due to the differences in predominant grass species and harvest timing protocols. Single degree-of-freedom contrast statements were used to determine significant differences among treatments. Critical time period for precipitation was considered to be April–September which provided the highest correlation with biomass production at the greatest number of locations.

Farmgate breakeven prices of biomass harvesting on CRP land were estimated by the following steps:

1. Constructed costs of biomass production for each N use rate, harvest timing, and location for each year over the study time period (Table 2).
2. Determined the farmgate biomass yields after incorporating a 7% loss of biomass during storage.
3. Divided the costs by the corresponding level of farmgate biomass yield to obtain the breakeven price of producing biomass with a particular harvest practice in \$ dry Mg^{-1}.

Four different cost scenarios were investigated. The first scenario (no opportunity cost) includes the total annual cost of production with no foregone opportunity costs for land rental payments included. The second scenario (reduced rental payment) includes production costs plus 25% of CRP land rental payment included as an opportunity cost during harvest years per USDA-FSA guidelines (USDA-FSA 2011). The third scenario (no rental payment) includes production costs plus full CRP land rental payment included as a foregone opportunity cost (i.e., CRP contract expires without renewal). The fourth scenario (opportunity cost of crop production) is similar to the third but instead of CRP payment costs it includes the foregone opportunity costs associated with net income from row crop production. Average land rental payment amounts for each state in 2011 (USDA-FSA, 2015) were used in total cost calculations for scenarios two and three. In scenario four, we estimate the breakeven price of biomass that landowners would need to prevent a conversion of land under CRP to row crop production. This requires the return to biomass production to cover not only the costs of producing the biomass but also the foregone net returns from producing the major crop in that county in 2007 dollars (as in Jain *et al*., 2010). The alternative crop is assumed to be wheat in MT, GA, and OK, and corn and soybean in MO, ND, and KS. The data of yield and state-level price for each alternative crop were published by the National Agricultural Statistics Service (NASS) in 2007 (USDA-NASS 2015). We assume that CRP land has one-third less productivity compared to cropland following the assumption in Hertel *et al*. (2010). As a result, when CRP acres are converted to crop production, they will achieve below-average crop yield. The associated production cost is estimated using information from crop budgets complied for that state by state extension services. Breakeven prices for biomass were analyzed by location in a mixed model with N rate, harvest timing and their interaction considered as fixed effects while year and block were considered as random effects. Least square means of fixed effects were compared when effects were significant at $\alpha = 0.05$ using the SAS pdmix800 macro (Saxton, 1998).

Results

Significance levels of a few variables at most sites were different when analyzed across all years of the study compared with analysis from the first 3 years as indicated by italics in Table 3. The N rate × harvest timing interaction was significant in MO when analyzed across all years of the study. This was due to yields at 56 kg N ha^{-1} not being different from those at 0 kg N ha^{-1} when harvested at the EGS timing in each of the last 3 years (2011–2013) which tended to be dry during the latter part of the season. The N rate × harvest timing interaction was not significant in OK when analyzed across years, whereas it was considered to be significant but not important during the first 3 years (Lee *et al*., 2013).

The year × N rate interaction was significant in KS, ND, and OK because the yield response at both 56 and 112 kg N ha^{-1} was much lower in the last 3 years (2011–2013) which were drier than the first 3 years (2008–2010). Harvest timing was significant in ND due to higher yields with EGS harvests compared with PSC in the latter 3 years of the study, whereas this was only true in 2009 during the first half of the study.

Nitrogen fertility had a significant effect on biomass yield at all locations when analyzed across all years of the study (Table 3). This was different from the results in MT during the first half of the study due to a flat yield response in 2008 and 2009. The N rate of 112 kg ha^{-1} produced the highest biomass yield at each location and so was considered an agro-

Table 2 Assumptions for costs of biomass production, CRP land rental payment, and row crop land rent for six locations

	GA	KS	MO	MT	ND	OK
N fertilizer price ($ kg^{-1})*	0.95	0.77	0.58	1.10	0.95	0.77
Fertilizer spreading ($ ha^{-1})†	9.26	9.26	9.26	9.26	9.26	9.26
Mowing ($ ha^{-1})‡	45.22	28.19	25.15	24.71	24.71	26.22
Baling ($ Mg^{-1})‡	24.58	16.43	18.55	13.56	13.56	24.02
Staging and loading ($ Mg^{-1})§	6.38	6.38	6.38	6.38	6.38	6.38
Storage ($ Mg^{-1})‖	3.22	3.22	3.22	3.22	3.22	3.22
Average land rental payment ($ ha^{-1})**	115.97	99.05	182.90	79.27	89.43	82.78
Average row crop land rent ($/ha^{-1})††	165.87	236.78	262.91	173.95	205.69	146.12

*Data obtained from Quick Stats (USDA-NASS 2015).
†Data obtained from Haque *et al*. (2009).
‡Actual custom service rates paid at each location.
§Data obtained from Duffy (2008).
‖Data obtained from Brummer *et al*. (2002).
**Average CRP land rental rates for each state in 2011 obtained from USDA-FSA (2014).
††In MT, GA, and OK, opportunity cost of cropland is based on the profit of leading crop, wheat, in 2007; in KS, MO, and ND, opportunity cost of cropland is based on corn–soybean profit in 2007.

Table 3 Probability values from the analysis of variance for biomass yield and economic analyses for 5 or 6 years at each of the CRP research sites*†

	Warm-season grass sites			Cool-season grass sites		
Source of variation	KS	OK	ND	MT	GA	MO
Biomass yield						
Year	<0.0001	<0.0001	*<0.0001*	<0.0001	<0.0001	*<0.0001*
N rate	<0.0001	<0.0001	<0.0001	*0.0108*	0.0001	<0.0001
Year × N rate	*0.0042*	<0.0001	*0.096*	0.1256	0.6222	0.9776
HT‡	0.0015	0.0074	*0.0126*	<0.0001	<0.0001	<0.0001
Year × HT	<0.0001	<0.0001	0.0002	<0.0001	<0.0001	*0.0005*
N rate × HT	0.2284	*0.2748*	0.3945	0.2249	0.8729	*0.0260*
Year × N rate × HT	0.9699	0.6879	0.5992	0.8450	0.9747	0.7373
Breakeven prices§						
No opportunity cost						
N rate	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0435
HT	0.0172	0.0162	0.0313	<0.0001	0.0472	0.0004
N rate × HT	0.1965	0.7085	0.1754	0.0248	0.1341	0.3269
Reduced rental payment						
N rate	0.0011	0.0002	<0.0001	<0.0001	0.0002	0.6958
HT	0.0157	0.0079	0.0354	<0.0001	0.0120	0.0003
N rate × HT	0.1728	0.8039	0.1894	0.0418	0.2092	0.1611
No rental payment						
N rate	0.1838	0.2598	0.1831	<0.0001	0.0249	0.1513
HT	0.0165	0.0004	0.0498	<0.0001	0.0008	0.0004
N rate × HT	0.1510	0.3737	0.2257	0.1321	0.4195	0.0750
Opportunity cost of crop production						
N rate	0.8826	0.9663	0.1354	0.0002	0.0931	0.0734
HT	0.0120	0.0003	0.0690	<0.0001	0.0002	0.0004
N rate × HT	0.1458	0.5883	0.2621	0.3187	0.5126	0.0651

*GA and MT were not harvested in 2013, and OK was not harvested in 2011.
†Probability values in italics represent changes in significance with analysis in 2008–2010 (see Lee *et al.*, 2013) compared with analysis of the full study.
‡HT, harvest timing.
§Breakeven prices for biomass under four scenarios: No opportunity cost: no loss of CRP land rental payment taken into account; Reduced rental payment: CRP land rental payment reduction of 25% during harvest years considered a foregone opportunity cost; No rental payment: CRP contract allowed to expire, and therefore, land rental payments are considered a foregone opportunity cost; Opportunity cost of crop production: net returns from the major crop (corn-soybean or wheat) considered as a foregone opportunity cost.

nomic best management practice (BMP) (Fig. 2a). Yields with 112 kg ha^{-1} were significantly higher than those with 56 kg ha^{-1} at all locations except KS and MT. Yields increased from 0 to 56 kg N ha^{-1} at all sites, although the difference was not significant at GA.

The year × harvest timing interaction was significant for MO when analyzed over the entire study but not during the first 3 years because the PSC biomass yields were slightly higher than those with the EGS harvest in 2013, although the difference between the two was not significant (Table 3; Fig. 3). Harvest timing with the highest biomass yield was site-specific and was a factor of predominant grass type, seasonal precipitation regime, and number of harvests taken per year. The EGS harvest timing produced the highest yields at GA and MO among cool-season grass sites and at ND and OK among warm-season sites (Fig. 2b). Yields at KS and MT were significantly higher with the PSC harvest timing. No pattern was observed over time between yields harvested at PSC and EGS with the exception of MO, which consistently produced higher yields in the EGS treatment except in 2013 (Fig. 3). The harvest timing considered to be an agronomic BMP was the one producing the highest yields at each respective site averaged over time. Mean yields under BMP were significantly greater (range of 0.3–1.7 Mg ha^{-1} higher) than yields averaged across treatments at each location (Fig. 4). Under BMP, biomass yields of 1.6–3.5 and 3.7–6.4 Mg ha^{-1} were recorded for warm- and cool-season

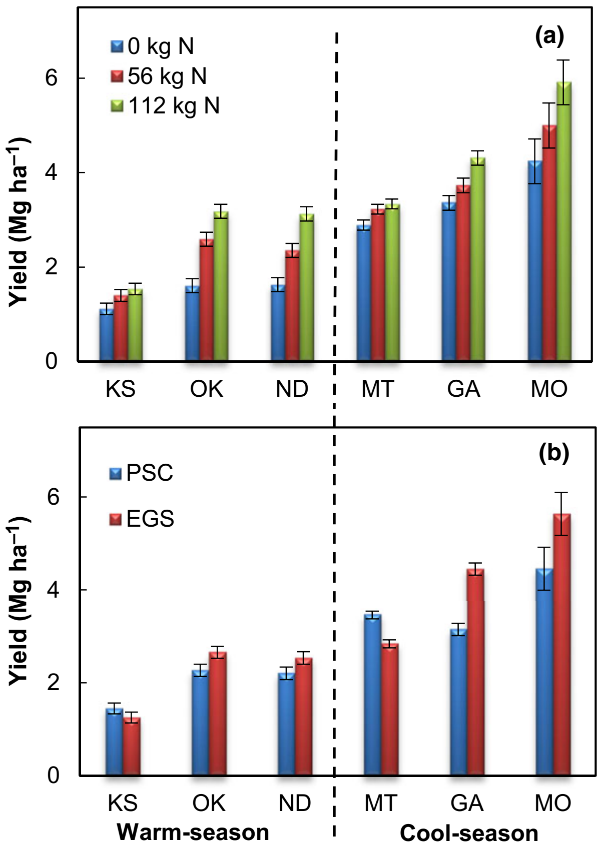

Fig. 2 Biomass yield as affected by (a) N rate and (b) harvest timing for CRP sites with predominantly warm-season or cool-season grass mixtures. Yields were averaged across all harvest years. Harvest timings included PSC (peak standing crop, at anthesis) and EGS (end of the growing season). Bars represent standard errors of the differences of means when analyzed by location ($\alpha = 0.05$).

mixture CRP land, respectively, when averaged over time.

Biomass yields tended to increase with increasing precipitation at most sites (Fig. 5), although the critical period for precipitation differed among sites. Precipitation amount at each site was a primary factor in annual yields. At KS, OK, and MT, the highest correlation between yield and precipitation was observed for the April–September period (Fig. 5). At MO, yield and precipitation during the entire growing season were not strongly correlated ($R^2 = 0.089$ and 0.315 for 0 and 112 kg N ha^{-1}, respectively, harvested at EGS), and the yield response was relatively flat (slope = 0.003 on average). However, the correlation was much better ($R^2 = 0.7213$ and 0.7571), and the yield response was higher (slope = 0.014 on average) for precipitation received during April–June (data not shown). At ND and GA, the correlations between yield and precipitation were very low and yield responses to precipitation were relatively flat. Aside from the decline in yields during drought years, no trend was observed with respect to yields over time (Fig. 3).

Nitrogen fertility rate significantly impacted the breakeven biomass price for all sites when no opportunity costs were included (Table 3). This was also true for all sites except MO when biomass is harvested periodically from CRP land with a 25% reduction in land rental payments. However, N rate was significant for only MT and GA when land was removed from the CRP, and the full rental payment was considered a foregone opportunity cost, and for MT when crop production was included as a foregone opportunity cost. Harvest timing significantly impacted breakeven prices under all scenarios at every location except at ND with row crop production included as a foregone opportunity cost. The N rate × harvest timing interaction was significant only at MT when no or partial land rent opportunity costs were included.

When no opportunity costs were assessed, breakeven prices for biomass at the farmgate were significantly lower when no N fertilizer was applied compared with 112 kg N ha^{-1} for all locations and significantly lower than 56 kg N ha^{-1} for all locations except GA and MO (Table 4). This was also true with 25% reduced CRP rental payments for all locations except MO where differences among N rates were not significant. No differences among N rates were found when the full CRP rental payment or revenue from crop production were considered a foregone opportunity cost for all sites except MT where costs were impacted by N rates similar to the other economic scenarios.

Significant breakeven price differences were found between the two harvest timings for all economic scenarios and locations except at ND when crop production opportunity costs were assessed and at GA with no or reduced CRP payment opportunity costs assessed. Biomass prices were lower when harvested at EGS at ND, GA, and MO and lower at PSC at KS, OK, and MT.

Discussion

The Conservation Reserve Program was originally established for soil and water conservation, not biomass production. However, CRP land is a potentially important resource for sustainable biomass feedstock production as major land-use change is not expected (Chamberlain *et al*., 2011; Clark *et al*., 2013). Accordingly, in order for CRP to be a reliable source of sustainable biofuel feedstock, BMP must be developed and followed. This study evaluated CRP grasslands as a herbaceous biomass source with potential use as a dedi-

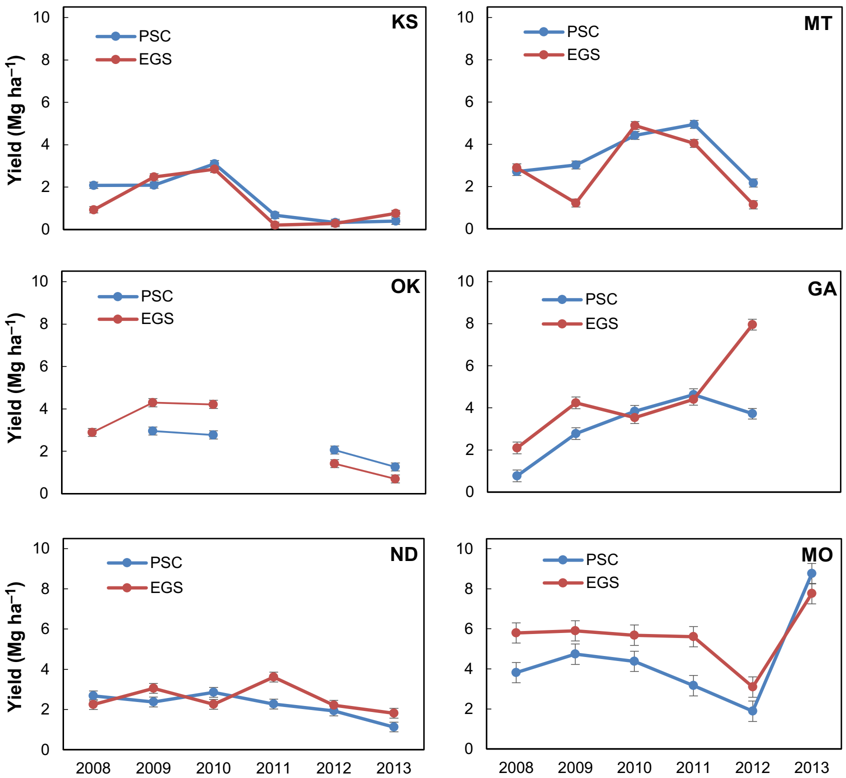

Fig. 3 Biomass yields from 2008 to 2013 averaged across N rates at warm-season (KS, OK, ND) and cool-season (MT, GA, MO) grass locations. Bars represent standard errors of the differences of means when analyzed by location (α = 0.05). Harvest timings included PSC (peak standing crop, at anthesis) and EGS (the end of the growing season).

cated bioenergy feedstock and well covered the range of CRP land distribution in the United States.

Nitrogen fertilization significantly increased biomass feedstock production, and adequate N application is crucial to obtaining the yields outlined by the Billion-Ton Update (USDOE 2011). Biomass yields significantly increased with increasing N fertilization rates at all locations. Differences between adjacent rates (0 vs. 56 and 56 vs. 112 kg N ha^{-1}) were not significant in every site-year, although differences between 0 and 112 kg N ha^{-1} were significant in all cases except when rainfall was severely limited. Nitrogen rate recommendations for perennial grasses grown for biomass are based in part on the long-term precipitation means for a given region. Vogel *et al.* (2002) recommended 120 kg N ha^{-1} for switchgrass (*Panicum virgatum* L.) grown in Nebraska and Iowa, while Brejda (2000) recommended 33–110 kg N ha^{-1} for areas with lower rainfall. Biomass yields did not significantly increase with fertilization rates higher than 56 kg N ha^{-1} in a mixture of switchgrass, big bluestem (*Andropogon gerardii* Vitman), and indiangrass (*Sorghastrum nutans* (L.) Nash) (Mulkey *et al.*, 2008) or in a switchgrass monoculture (Mulkey *et al.*, 2006) in central South Dakota where precipitation is generally limited.

Harvest timing management did not have much impact on long-term biomass production. No trend was observed with respect to yield response to harvest timing over the course of the study except at MO where EGS produced consistently higher yields than PSC except in 2013. Precipitation at MO was much lower than normal from June onward in 2013 which impacted biomass production for the later spring harvest (27 June) more than the earlier spring harvest (4 June) (Table 1). Both the PSC and EGS treatments in MO included a spring and a fall harvest, the difference being the later timing of the spring harvest for the latter treatment. This two-cut system for the cool-season mixtures allowed for a more consistent response to the difference in harvest timing and provided a buffering effect against weather variability. Reynolds *et al.* (2000) in eastern Tennessee and Richner *et al.* (2014) in Missouri also found that a two-cut system produced the highest aboveground biomass yields in switchgrass, although the N removal rate was also significantly higher than in a one-cut system when rainfall was not severely limited.

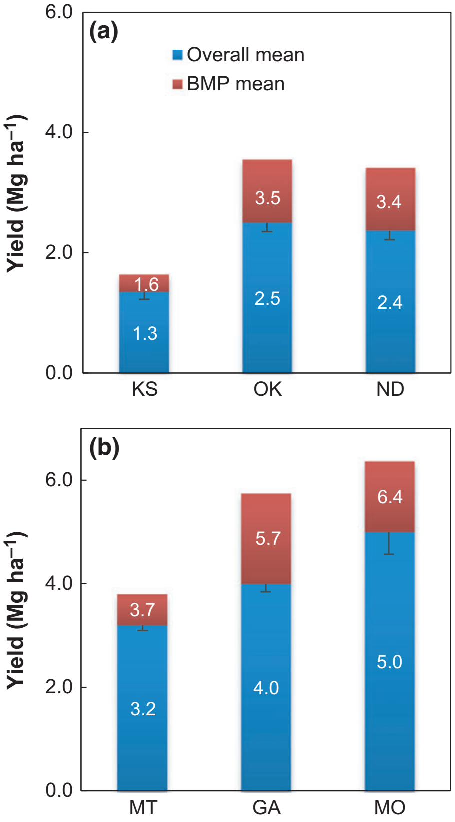

Fig. 4 Biomass yields at (a) warm-season and (b) cool-season grass locations. Overall mean yields were averaged across years, N rates, and harvest timings while best management practices (BMP) were site-specific and based on the harvest timing and N rate with the highest mean biomass yield over time. Bars represent standard errors of the differences of means when analyzed by location (α = 0.05).

Although biomass yield was consistent under different harvest regimes, delaying harvest until after a killing frost or at the end of the growing season is generally recommended for stand longevity for warm-season species. Biomass harvests conducted after a killing frost yielded slightly lower than when harvested in early October in northwestern Oklahoma; however, percent moisture and N removal decreased with the later harvest (Venuto & Daniel, 2010). Anderson *et al.* (2013) found that delaying harvest until after a killing frost (late fall through early spring) resulted in lower biomass yields compared with a late summer harvest, but moisture content and ash and protein concentrations were all significantly lower while cellulose, hemicellulose, and lignin were higher with the later harvest.

The inability to detect a trend over time with regard to harvest timing at other locations is likely due in part to the dry conditions experienced at most locations during the latter half of the study. Precipitation during the growing season was a critical factor for annual biomass feedstock production across all regions, and annual feedstock production was severely reduced when growing season precipitation was below 50% of average. For example, in KS and OK, the drought severely impacted crop growth beginning in 2011, and the effects appeared to persist throughout the remainder of the study. The effect of weather likely masked the effect of harvest timing similar to the situation with N fertility.

Biomass yields during the first 3 years (2008–2010) were much higher than those during the last 3 years (2011–2013) for all locations except GA. The main reason for low biomass yield during the latter period was lack of precipitation during the growing season (April through September) (Figs 1 and 5). In particular, limited biomass yields in KS and OK during 2011 through 2013 were caused by severe drought in the Great Plains region.

A lack of precipitation has been linked with reduced photosynthetic rates in switchgrass (Wullschleger *et al.*, 1996; Sanderson & Reed, 2000). Sanderson & Reed (2000), however, found that water stress did not always result in lower biomass yield in central Texas, possibly due to abundant spring precipitation and because the interval between precipitation events during the summer was not long enough to affect plant yields. Lee & Boe (2005) found that switchgrass biomass yields were highly variable but that April–May precipitation explained >90% of the variation over a four-year period in central South Dakota when precipitation was below average. On native rangelands surrounding the KS location, combined May and June precipitation accounted for 56% of the variation in growing season dry matter production (Harmoney & Jaeger, 2013). The lack of correlation between yield and precipitation in GA was possibly because water was not limiting with precipitation levels between 280 and 800 mm during the growing season each year of the study (Fig. 5). However, in ND, the lack of correlation was more likely an effect of generally poor soil fertility at that site, although soil fertility factors were not monitored during the study, with the result that biomass yields much higher than 4 Mg ha^{-1} are considered unlikely regardless of precipitation levels.

The breakeven farmgate prices of biomass harvested on CRP land increased significantly as N application rate increased for all six sites under most opportunity cost scenarios (Table 4). Geographically, MT had the lowest costs of biomass production followed by ND, MO, OK, GA, and KS when no N was applied and no opportunity costs were included. When N was applied at 56 or 112 kg ha^{-1}, MO had the lowest costs of biomass production because of its high biomass yield response to N application while KS remained consistently the most costly place for biomass harvesting among the six study sites. The high cost in KS was due

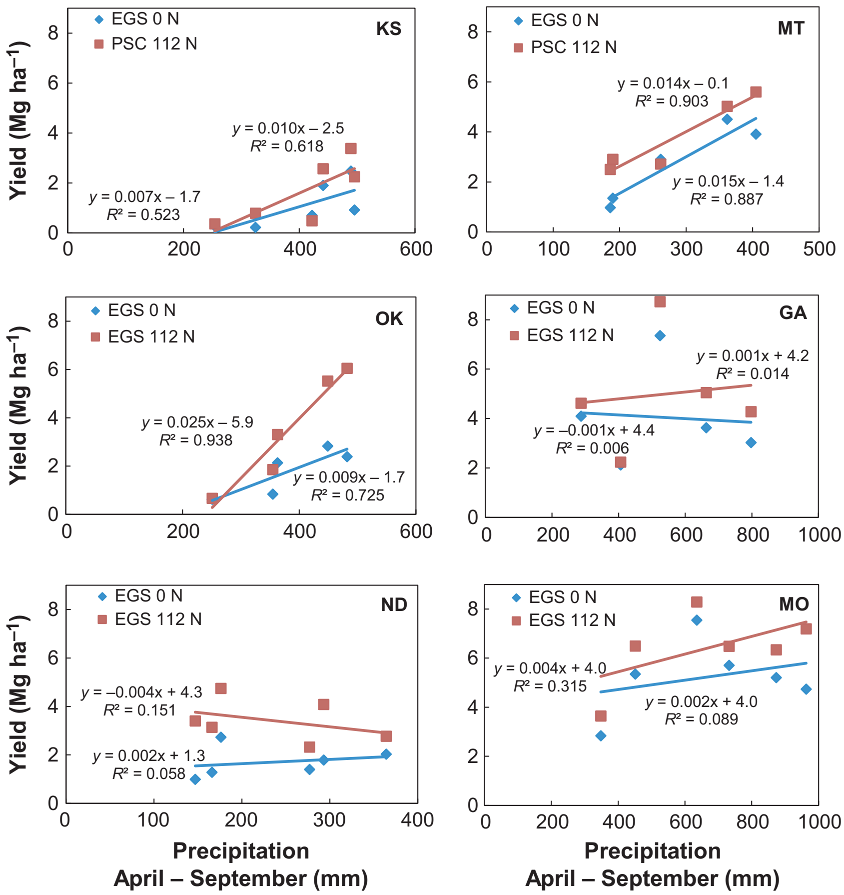

Fig. 5 Yield response with standard practices (♦, EGS 0 N) and best management practices (■) at each CRP site with predominantly warm-season grass mixtures (KS, OK, and ND) and cool-season grass mixtures (MT, GA, and MO) and the linear relationship with precipitation during the growing season. Each data point represents a mean for an individual year. Nitrogen rates given in kg N ha^{-1}. PSC: peak standing crop, at anthesis; EGS: harvests occurring at the end of the growing season.

to very low harvests in the latter 3 years of the study as discussed earlier, resulting in average total production costs of \$74 and \$294 Mg^{-1} for 2008–2010 and 2011–2013, respectively.

As discussed earlier, harvested biomass yields illustrate a clear response to N application for most study sites. However, our results show that the N-induced increase in biomass yields is not large enough to offset the incremental costs entailed from the purchase and application of N fertilizer. A more detailed examination showed that the costs of N application across the study sites ranged from \$44.22 to \$75.31 ha^{-1} and \$79.17 to \$141.36 ha^{-1} for 56 and 112 kg N ha^{-1}, respectively (data not shown). Compared with the no N application case, the N-induced costs imply an increase in the total operating costs of biomass harvesting by 22–126% and 54–225% in the 56 and 112 kg N ha^{-1} cases, respectively, depending on location. However, the corresponding N-induced increases in harvested biomass yields relative to the 0 kg N ha^{-1} case were only 11–61% and 15–98% in the 56 and 112 kg N ha^{-1} cases, respectively—substantially lower than the increase in costs of biomass harvesting due to N application.

Conservation Reserve Program land owners are economically incentivized to harvest biomass on their grassland at the timing that produces the highest yields. However, for a variety of reasons—to ensure stand longevity by allowing translocation of nutrients to overwintering plant structures, to allow dry-down of standing biomass prior to harvest, to extend the period of wildlife cover, etc.—farmers may have other incentives to harvest at EGS. As biomass breakeven prices were minimized with no N fertilizer application, it is of interest to compare the breakeven price under different economic scenarios for biomass with 0 kg N ha^{-1} and harvested at EGS. Given the high breakeven prices when full CRP land rental payments are included as foregone opportunity costs (e.g., \$105 Mg^{-1} on average for MT where costs were the

Table 4 Breakeven prices (\$ Mt^{-1}) for biomass analyzed by location under four economic scenarios as affected by harvest timing and nitrogen fertility

Effect	Level	No opportunity cost* †	Reduced rental payment	No rental payment	Opportunity cost of cropland
Warm-season grass					
KS					
HT‡	PSC	151 b	194 b	322 b	559 b
	EGS	217 a	275 a	448 a	768 a
N rate	0	94 B	150 B	319 ns	633 ns
	56	200 A	251 A	402 ns	683 ns
	112	258 A	302 A	432 ns	675 ns
OK					
HT	PSC	72 b	83 b	114 b	161 b
	EGS	88 a	103 a	160 a	205 a
N rate	0	57 C	74 C	123 ns	181 ns
	56	82 B	92 B	144 ns	186 ns
	112	102 A	112 A	143 ns	182 ns
ND					
HT	PSC	73 a	86 a	125 a	193 ns
	EGS	65 b	76 b	112 b	174 ns
N rate	0	45 C	61 B	110 ns	195 ns
	56	76 B	88 A	124 ns	187 ns
	112	85 A	94 A	122 ns	169 ns
Cool-season grass					
MT					
HT‡	PSC	60 b	67 b	88 b	122 b
	EGS	79 a	90 a	122 a	174 a
N rate	0	39 C	49 C	78 C	124 B
	56	70 B	79 B	105 B	146 B
	112	99 A	107 A	133 A	174 A
GA					
HT	PSC	98 ns	114 ns	161 a	189 a
	EGS	83 ns	91 ns	117 b	130 b
N rate	0	65 B	78 B	116 B	138 ns
	56	94 B	106 A	144 AB	162 ns
	112	112 A	123 A	158 AB	178 ns
MO					
HT	PSC	63 a	81 a	134 a	165 a
	EGS	51 b	61 b	92 b	109 b
N rate	0	53 B	72 ns	129 ns	167 ns
	56	56 AB	68 ns	103 ns	124 ns
	112	63 A	73 ns	106 ns	125 ns

*No opportunity cost: no loss of CRP land rental payment taken into account; Reduced rental payment: CRP land rental payment reduction of 25% during harvest years considered a foregone opportunity cost; No rental payment: CRP contract allowed to expire and therefore land rental payments are considered a foregone opportunity cost; Opportunity cost of cropland: net returns from major crop (corn–soybean or wheat) considered as a foregone opportunity cost.
†Lower case letters denote significant differences between harvest timings and upper case letters between N rates for each location; mean separation conducted at $\alpha = 0.05$.
‡HT, harvest timing; PSC, peak standing crop; EGS, end of growing season; N rates in kg ha^{-1}.

lowest), CRP land owners are unlikely to have the economic incentives to allow a CRP contract to expire in order to harvest biomass annually unless biomass prices were very high. The situation is similar when considering row crop production revenue a foregone opportunity cost. When no opportunity costs were assessed, breakeven prices ranged from \$41 to \$67 Mg^{-1} for all sites except KS (\$92 Mg^{-1}) when averaged across years. When a 25% reduction in CRP payments was included, breakeven prices ranged from \$52 to \$81 Mg^{-1} for all sites except KS (\$147 Mg^{-1}). Breakeven prices under the 25% rental payment reduc-

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tion scenario are 26–39% lower than the scenario foregoing full rental payment but 14–27% higher than those with no opportunity cost assessed for all locations when averaged across all treatment variables.

In contrast to the high breakeven prices needed for harvesting the naturally growing biomass from CRP acres, previous studies have shown that high-yielding perennial energy grasses like switchgrass and miscanthus (*Miscanthus* × *giganteus* Greef and Deuter ex Hodkinson and Renvoize) could be grown at much lower breakeven prices (Miao & Khanna, 2014). Using CRP land rental payments as the opportunity cost of producing miscanthus and switchgrass in these counties, Miao & Khanna (2014) find that breakeven prices would range between \$43–60 Mg^{-1} for switchgrass and \$40–96 Mg^{-1} for miscanthus.

Our results have implications for CRP land rental payment and cost management under the influence of biofuel and climate policies currently being pursued in the United States. The total cost for the government of the CRP in the six study states was \$377 million in 2014 (USDA-FSA, 2015). If biomass was to be harvested on CRP land with the 25% rental payment reduction, the total cost of the CRP in the six states together could be reduced by \$31 million annually (assuming only one-third of the acreage would be harvested in a given year per the current rules), suggesting an annual reduction in CRP costs for the government of 8.2%. This reduction in cost for the government would, however, be offset by the increased costs of production incurred by growers. Although this scenario would generate only one-third of the potential biomass for the developing cellulosic bioenergy industry, it would allow for the utilization of otherwise unharvested lands and likely provide economic benefits for land owners, biomass processors and the U.S. government.

This six-year field experiment has demonstrated the importance of long-term farm-scale research for estimating the biomass feedstock production potential of CRP grasslands. This is highlighted by the fact that, by far, the greatest impacts on seasonal biomass production were due to location-specific precipitation. The results presented here demonstrate that CRP land is a potential resource for bioenergy feedstock production if the appropriate management practices are followed under normal precipitation during the growing season. These results will provide a base of information for a projection of feedstock production in CRP land for economic analysis.

Based on the biomass yield and economic data collected during this study at six different CRP sites across the United States, we show that the use of N for yield enhancement unambiguously increased the farmgate unit price of biomass regardless of the timing of harvest for all six study sites. We also find that if the net revenue from biomass harvesting can be used to reduce CRP land rental payments received by land owners without compromising their economic welfare, we estimate that the current CRP rental rate for the six study states can be reduced by over 8% on average, leading to significant saving in the costs of the CRP for the government. However, such a scenario would require relatively high biomass prices at most study locations which does not seem likely in the near future.

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